Remotely Sensed Tropical Cyclone Structure/Intensity Changes

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LONG-TERM GOALS

Routinely map the life cycle of a tropical cyclone's (TC) three-dimensional (3-D) structure and intensity changes via satellite remote sensing data for both real-time analyses and as input to numerical weather prediction (NWP) models.

OBJECTIVES

Develop accurate automated techniques to estimate TC intensity and intensity changes under all conditions (e.g., 24 hr/day, any global location, tropical depression to Category 5). Map TC inner-core structure changes and provide consistent basis for understanding related storm intensity changes that have proven difficult to comprehend with limited aircraft recon data sets.

APPROACH

Passive and active microwave satellite data will be used to mitigate the inherent limitations of visible and infrared (vis/IR) data used to monitor TC structure and intensity worldwide. The Dvorak technique has provided the bulk of the global TC intensity estimates for the past 30+ years and significantly enhanced the TC monitoring system. However, the technique is inherently limited by the fundamental inability of IR data to see-through upper-level clouds that obscure inner-storm TC structure. Thus, IR-based Dvorak intensity estimates typically can't handle eyewall cycles and rapid intensification since IR data frequently has no clue eyewall change is ongoing.

This effort will incorporate passive microwave imager data from the current suite of operational and R&D including: three Special Sensor Microwave/Imagers (SSM/I) onboard the Defense Meteorological Satellite Program (DMSP) satellites (F-13, 14, 15), the NASA Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI), the Advanced Microwave Scanning Radiometer (AMSR-E) on NASA Aqua, the Coriolis Windsat polarimetric radiometer, three Advanced Microwave Sounding Units (AMSU) on NOAA polar orbiters (N15/16/17), the Microwave Humidity Sounder (N-18), and the Special Sensor Microwave Imager Sounder (SSMIS, F-16). We will acquire and process all sensors when overflying TCs globally to collect and study applications on TC monitoring (track and intensity).

Report Documentation Page

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We will utilize 85-89 GHz and 37 GHz passive microwave imager data to map TC structure, with particular focus on inner-core dynamics and eyewall cycle processes. The "microwave constellation" will permit us to understand much of the temporal changes each TC undergoes even though no geostationary microwave sensor currently exists.

The unique TC structural information observed with microwave sounder data will be exploited to extract a TC's vertical temperature structure that is highly correlated with intensity. This project will take advantage of the "all weather" microwave data sets to extract accurate TC information when vis/IR data are cloud-limited. Methods will be tested to extract storm intensity from both imagers and sounders separately and combined into merged algorithm as validation data sets permit more mature methods which highlight the various pluses and minuses attached with each effort.

Use the microwave imager's ability to map atmospheric moisture very accurately to investigate the relationship between the Saharan Air Layer (SAL) and TC intensity. SAL events are characterized by a huge "pulse" of dry, stable, and often dusty air that has been difficult to monitor in the past. Several remote sensing methods now exist that attempt to track SAL outbreaks from genesis and westward through the tropical Atlantic.

WORK COMPLETED

SSM/I passive microwave digital imagery from over 10,500 tropical cyclone overflights has been processed at NRL-MRY and document eyewall replacement cycle characteristics, including storm intensity fluctuations and frequency. The data processing techniques utilize specific image enhancement methods that produce high quality outputs. TC eyewall cycles have been documented using 1997-2005 data sets not possible with earlier studies. The Tb and rainrate products are analyzed by an automated computer vision technique using specific feature screening criteria.

An enlarged data set is nearing completion for use in deriving a passive microwave image TC intensity algorithm. This Atlantic basin data set will take advantage of NOAA/AF hurricane hunter validation using dropsonde derived minimum sea level pressure (MSLP).

Four seasons of satellite total precipitable water (TPW) products have been produced for the Atlantic basin. The near real-time data sets were produced 4/day and routinely used by NOAA G-IV planners to locate very stable and dry Saharan Air Layer (SAL) air masses near TCs and were a key NOAA/HRD tool in Hurricane Debby and Helene SALEX field program flights.

TECHNICAL RESULTS

Eyewall replacement cycles:

This 6.2 effort has pioneered a new view of TC structural evolution. The inability to routinely "see through" upper-level clouds obscuring eyewall and rainband formation greatly hindered our knowledge of internal storm organization and thus intensity. Infrequent examples seen via aircraft (mainly Atlantic basin) and land-based radar (NEXRAD) and more recently foreign radars via Internet distribution left the TC community with a poor understanding of inner-core structural fluctuations and related storm intensity trends. Passive microwave data from the SSM/I, TMI, AMSR-E, SSMIS, WindSat, and AMSU on the NRL-MRY tropical cyclone web page were used to create a database

(Hawkins, et al., 2006, and Hawkins, et al., 2001) in addition to a specially processed SSM/I database. The NRL TC web page can be located at: http://www.nrlmry.navy.mil/tc-pages/tc_home.html

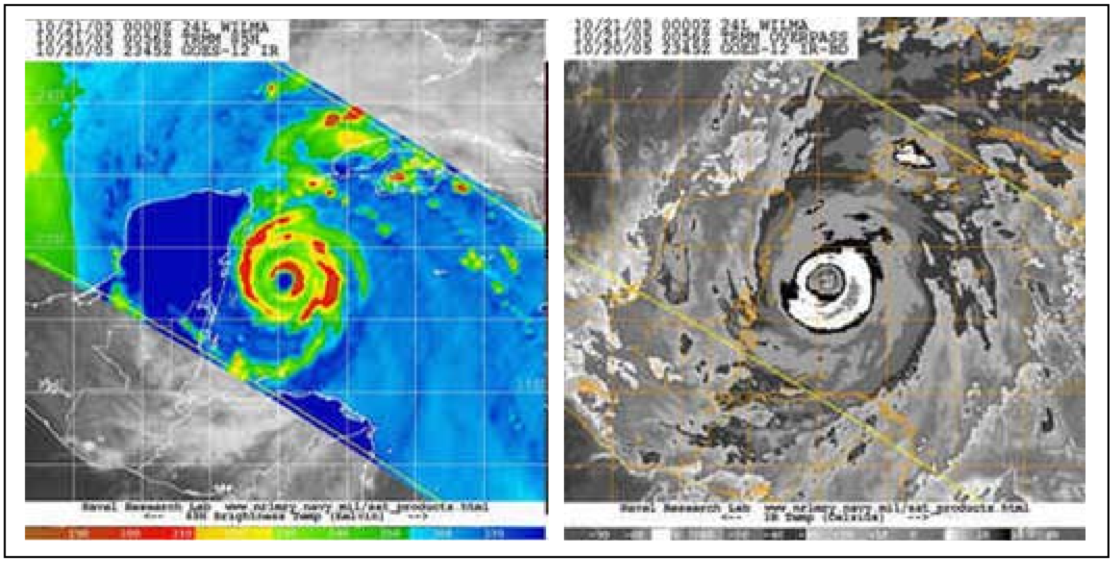

Figure 1. Coincident Hurricane Wilma IR Dvorak enhancement (right panel) and TMI 85 GHz H-pol brightness temperatures (Tb, left panel) near 0000 GMT 21 October, 2005 illustrating inability of IR data to view double eyewalls clearly seen with passive microwave data. Grid lines are 2 deg x 2 deg.

This structural evolution was highlighted in three 2005 Atlantic basin hurricanes (Katrina, Rita and Wilma) as each storm clearly exhibited double or concentric eyewalls while achieving Category 5 intensity. A double eyewall configuration was maintained till landfall for both Katrina and Rita, while Wilma hit Florida after the inner eye dissipated and one large diameter eyewall brought widespread damage over much of south Florida.

A systematic review of passive microwave data from 1997-2005 (Fig. 2) reveals that concentric eyewalls are highly correlated with storms reaching 120 kts or higher (Hawkins et al, 2006). 70% of Atlantic basin storms and three-quarters (80%) of western Pacific typhoons reaching best track intensities of 120 kts or more exhibited double eyewalls. These statistics can vary dramatically during any given year and/or basin, since intense storm numbers fluctuate with synoptic scale environmental conditions. For example, the wealth of 2005 Atlantic Cat 5 storms with concentric eyewalls raised the 9 year percentage from 60% to 70%.

A key aspect of eyewall replacement cycles (ERC) is the short term intensity changes that directly mirror the inner storm structure changes. NRL passive microwave data in near real-time has enabled NHC/JTWC to routinely include this critical knowledge of eyewall structure into their short-term intensity trend forecasts. The story is not complete yet since we do not know whether a given storm will complete an ongoing ERC or if it will stop in midstream due to a variety of unfavorable environmental factors: wind shear, land, dry air entrainment, cool SSTS, etc. In addition, ERCs may

last for days or in occur in less than a day as rapid intensification speeds up the process and potentially catches us under prepared. Understanding the dynamical processes responsible for these remotely sensed structure changes will permit enhanced TC warnings.

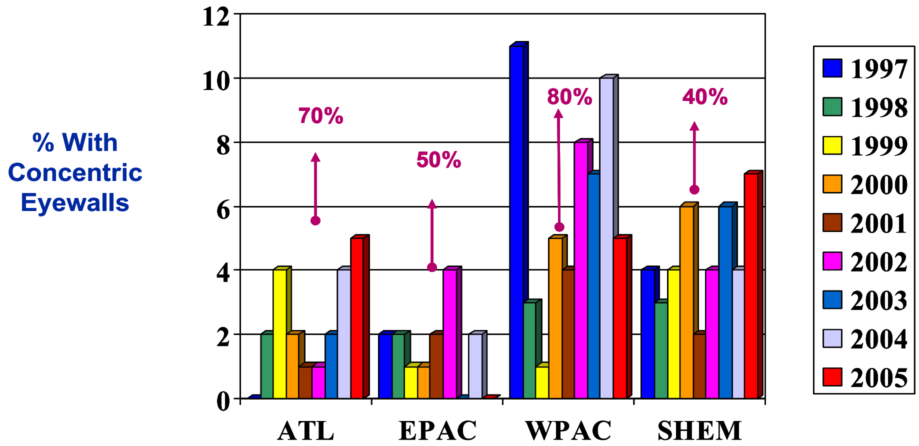

Figure 2: Number of tropical cyclones reaching a maximum sustained wind speed equal or greater to 120 kts for the Atlantic, Eastern Pacific, Western Pacific and southern hemisphere within 1997-2005. Approximately 70% of storms reaching 120 kts developed concentric eyewalls in the Atlantic, 50% in the eastern Pacific, while the western Pacific statistics reveal ~ 80% and SHEM 40%.

Saharan Air Layer:

Satellite remote sensing retrievals have only recently exposed the tropical Atlantic as a stark mix of moist tropical air and dry, stable and dusty Saharan air layer (SAL). SAL air masses are characterized by an intense inversion at 850-900 mb that inhibits convection and bulges out past the Cape Verde islands while beginning a 7-14 day journey towards the Caribbean islands and often the US east coast. SAL air stability can act as a “governor” on TC intensity if it becomes well entrained into a TC’s inner circulation. The impact can vary from little (if TC is intense and little inflow is permitted to the inner core), to modest (TC has ongoing battle between some SAL air inside versus moistening of SAL air by oceanic convection nearby), and lastly severe (SAL air shuts down inner convection as dry air inversion cuts off upward buoyancy).

Several satellite tools have been created within this project to monitor SAL events and track them during their evolution and potential interaction with tropical cyclones in various stages of formation, maintenance and decay: a) passive microwave imager/sounder derived total precipitable water (TPW) retrievals, b) aerosol optical depth (AOD) products using MODIS/AVHRR data sets, and c) MODIS dust enhancement products near the west African coast.

NRL has teamed up with Jason Dunion from NOAA’s Hurricane Research Division (HRD) during the summers of 2003-2006 to create a near real-time monitoring product (Dunion, et al, 2006). Three operational SSM/Is and one SSMIS are used to map the total precipitable water (TPW) across the Atlantic basin every six hours. SAL air is identified by TPW values less than ~ 50-60 mm, since non-SAL air has a very moist profile extending well above the typical SAL inversion. Fig. 3 maps SAL air being entrained from the north (blue colors) and wrapping into the storm from the southwest. High

TPW retrievals (orange-brown) denote the central storm region and the tropics to the south. Four/day TPW products can effectively monitor SAL transits across the basin in combination with additional satellite products.

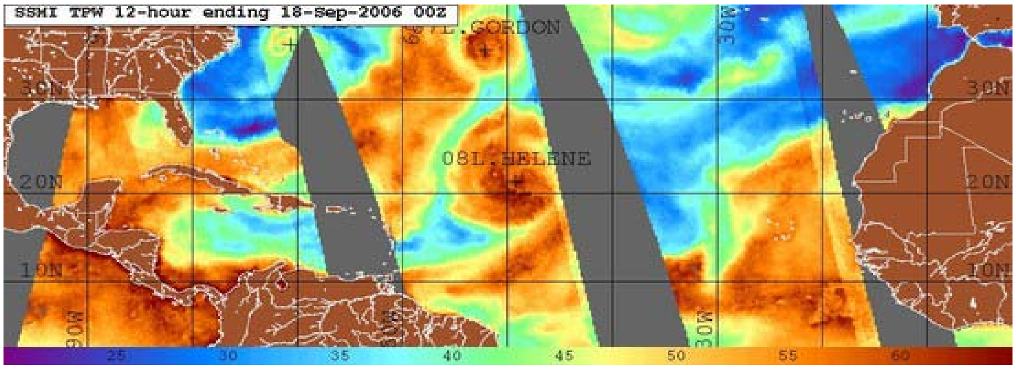

Figure 3: Composite Atlantic-basin TPW product using SSM/I passive microwave data for the 12 hours preceding 1200 GMT, Sept. 18, 2006. Low TPW values in blue-green are wrapping around Helene on the west and SW side while a new SAL wave is to the east.

Aerosol optical depth (AOD) retrievals via satellite visible imagers enable us to map the aerosol rich environment that typically characterizes SAL air masses. The wealth of dust and other particulates elevates the optical depth values from the relatively "clean" tropical surroundings and provides a means to "tag" SAL air. NRL created AOD basin-wide mosaics using NASA MODIS to assist in the HRD field program and also the NASA AMMA DC-8 missions from Cape Verde islands. Fig. 4 highlights one example of high AOD values residing NW of Helene on Sept. 14, 2006. Dusty SAL air with high AOD values is located between Florence to the north and Helene to the southeast. Subsequent AOD products reveal the bulk of the SAL air continued westward while Helene moved northward, wrapping some SAL air around it as noted in Fig. 3 above.

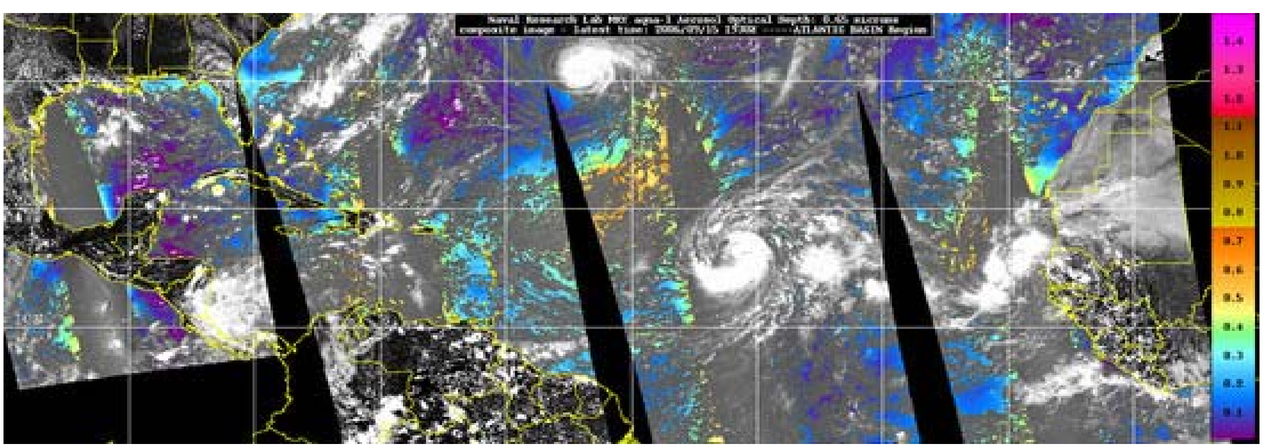

Figure 4. Aerosol optical depth (AOD) Atlantic-basin composite for Sept. 14, 2006 from 4 MODIS passes. Dust laden air marked in yellow-orange colors. Courtesy Mr. Arunas Kuciauskas.

MODIS digital data sets can also be used to highlight dust via the patented NRL dust enhancement algorithm (Miller et al, 2006) when applied to data near the West African coast. The dust algorithm works quite well in the eastern Atlantic basin since SAL air contains a significant dust "load" while so close to the Saharan dust source. Fig. 5 illustrates how the dust enhancement can highlight dust (pink) pulsing away from the African continent within the SAL event. In this example, 700 mb NOGAPS winds are overlain on top of the "dust enhancement" imagery to assist the user in denoting the low-level SAL jet typically found on the southern boundary of strong SAL events. Wind barbs are color coded according to the color wedge in the bottom right of Fig. 5, with yellow vectors representing winds of 20-20 kts.

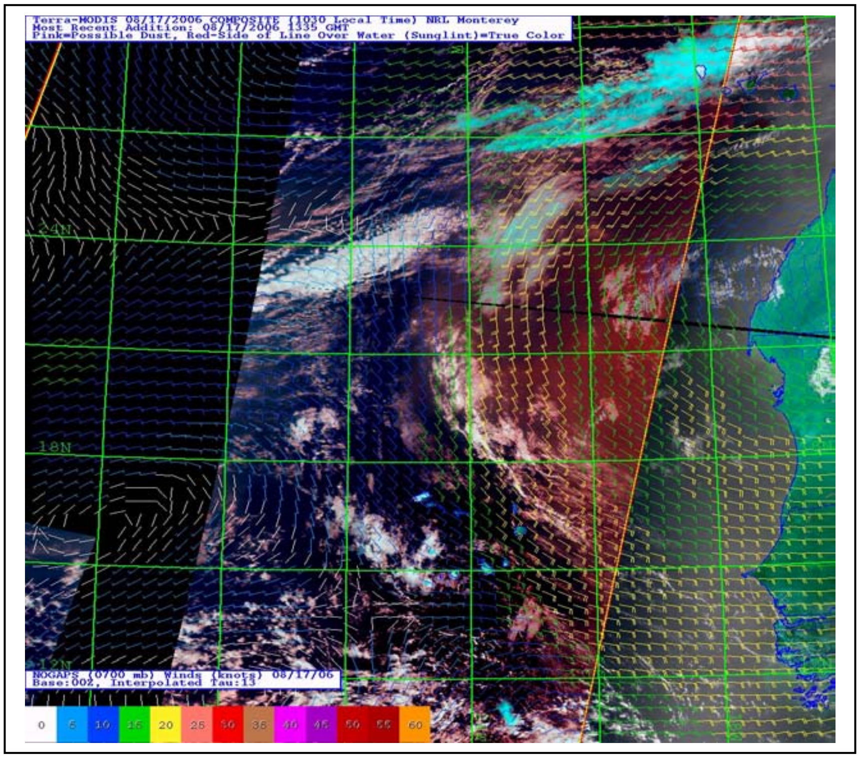

Figure 5: NRL MODIS dust enhancement product for 1030 GMT, August 17, 2006 denoting dust laden air in "pink" and 700 mb NOGAPS wind vectors overlain and color coded by wind speed. Courtesy Dr. Steve Miller.

The entire suite of NRL SAL monitoring satellite products are used in near real-time by the HRD G-IV jet and P-3 aircraft in order to plan and modify flight tracks and dropsonde locations in order to target SAL air around both Debby and Helene. NASA's AMMA DC-8 carried out similar efforts in the eastern portion of the basin.

IMPACT/APPLICATIONS

The concentric eyewall findings revealed in this 6.2 study have stimulated a large effort by dynamic meteorologists and the NWP community to understand the physical mechanisms responsible for creating eyewall replacement cycles (ERC). The ability to map SAL air routinely via satellite has provided a whole new look to isolated radiosonde data that now agrees with our new understandings,

since the spatial context has taken on a completely different perspective. SAL interactions with TCs are now recognized as an important TC intensity consideration.

TRANSITIONS

The SAL TPW and AOD products are used extensively by the NOAA-HRD G-IV and dropsondes from this aircraft are helping HRD/NRL/NHC understand SAL/TC interactions. The utility of the TPW and AOD efforts has been transitioned to the 6.4 SPAWAR Multi-sensor work unit and they are now a routine part of the NRL "Tropics" satellite web resource.

RELATED PROJECTS

This project is closely related to a 6.4 effort sponsored by the Space and Naval Warfare Systems Command (PEO C4I&Space/PMW-155) entitled "Tropical cyclone intensity and structure via multi-sensor combinations", funded under PE 0603207N. The 6.4 project serves as the transition vehicle, works closely with JTWC and the National Hurricane Center and serves as the conduit to new products at FNMOC. Feedback from JTWC, NHC and the TC research community has been extremely positive as evidenced in recent technical conferences.

This project works closely with understanding the needs of JTWC/NHC and FNMOC. Feedback is routinely solicited from all operational partners in order to understand how the 6.2 efforts outlined here can best be aligned to answer real world requirements and needs.

SUMMARY

A suite of NRL passive microwave products has greatly aided our understanding of tropical cyclone inner-core structure and eyewall replacement cycles (ERC). Double eyewalls are much more prevalent than thought until a few years ago due to our inability to see through upper-level clouds in earlier vis/IR imagery. This progress would not have been possible without the constellation of operational and R&D passive microwave satellites proactively utilized by NRL and shared via internet web pages.

The effort to map Saharan Air Layer (SAL) via both passive microwave and visible channel digital data provides new resources to effectively monitor SAL evolution during the basin-wide westward journey. Subsequent interactions with TCs can now be more closely studied and steps in understanding how their impede TC intensity formulated and tested in near real-time. The vertical integration of the ONR 6.2 effort with the SPAWAR 6.4 work unit has enabled rapid progress and transition of these remote sensing TC monitoring tools.

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